SCIENTIFIC REPORT

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Sub-barrier fusion cross section for superheavy nuclei

The cross section for the synthesis of superheavy nuclei is calculated within the hypothesis that the final compound nucleus must be obtained in the ground state. This initial request comes out from the fact that superheavy nuclei are synthesized in a very unstable final state, which leads to the rapid decay, by alpha emission, of these new, very heavy systems. This is due to the fact that the kinetic energy usually exceeds the Coulomb barrier. The result is an excited state for the final nucleus, and consequently a short alpha decay or fission halflife. If the final nucleus is obtained in the ground state, no additional excitation is present and the system will obviously live longer.

The fusion-like geometry used in this work is of tip-to-tip type, which is described by two spheroids partially overlapped during the fusion process. The symmetry axis is along the large semiaxes of the reaction partners. This choice ensures the lowest deformation barrier along the overlapping process. Any rotation driving out the system from axial symmetry increases the Coulomb part beyond synthesis usefullness. Such a configuration has as free parameters: charge and mass asymmetries, the deformation parameter of the target which is the ratio of the two spheroid semiaxes, the small semiaxis of the projectile b_P and the distance between centers R. This set of free parameters generates a multidimensional grid of possible deformations. Every point of the grid is then populated with the dynamical quantities necessary for the calculation of the cross sections.

In order to establish the formula for the cross section in such a process one starts from the basic definition:

$$\sigma = \frac{number.of.reactions/nucleus/sec}{number.of.incident.particles/cm^2/sec}(cm^{-2}, b) \tag{1}$$

which leads to the two important terms:

$$\sigma(E) = \pi\lambda^2 \cdot T(E) \tag{2}$$

where $\pi\lambda^2$ is the area covered by deBroglie wavelength and $T(E)$ is the probability for a particle flux of energy E to reach the surface of the target and react. Usually this term is calculated only up to the touching point configuration, ignoring the overlapping part of the process. Since this project calculates sub-barrier fusion processes, the barrier is formed mainly beyond the tangent point, up to the compound nucleus configuration. This idea leads to the identification of the transmission factor $T(E)$ with the probability for the projectile to tunnel the potential barrier E_{def} formed by the Coulomb and nuclear forces, when approaching with the energy E_{TP}.

$$T(E) = P(E, E_{TP}) \tag{3}$$

The deBroglie wavelength is now

$$\lambda = \frac{\hbar}{(2\mu_{TP}E_{TP})^{1/2}} \tag{4}$$

The request to obtain the final compound nucleus in the ground state suggests the kinetic energy value: as the two reaction partners are supposedly infinitely remoted, their equilibrium energy is the sum of their masses. At the end of the process they must reach the compound nucles energy. The difference between the two values is exactly the reaction energy Q_{TP}, hence the deBroglie wavelength:

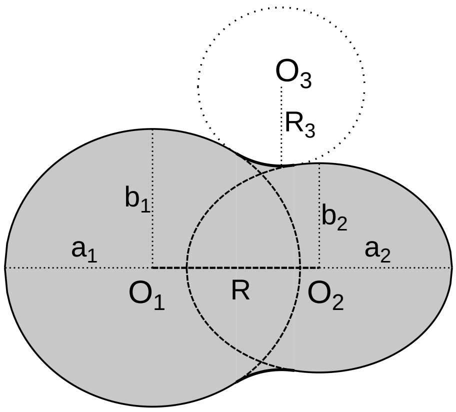

Figure 1: Fusionlike configuration for two spheroidal target and projectile nuclei. The free geometrical parameters (the semiaxes of the two spheroids and the distance between centers) are marked.

$$\lambda = \frac{\hbar}{(2\mu_{TP} Q_{TP})^{1/2}} \tag{5}$$

The barrier to be tunneled is now:

$$E - E_{TP} = E - Q_{TP} = E_b \tag{6}$$

where the barrier energy is the total deformation energy scaled at the ground state of the final nucleus.

The transmission factor is identified with the penetrability through the barrier.

In the WKB approximation the penetrability reads:

$$P = exp(S) \tag{7}$$

where the actions S is:

$$S = -\frac{2}{\hbar} \int_{(fus)} [2(\sum B_{ij} dq_i dq_j) E_b(q)]^{1/2} dq \tag{8}$$

Finally the cross section for a certain T-P pair is:

$$\sigma(E_b, TP) = \frac{\pi \hbar^2}{2\mu_{TP} Q_{TP}} exp(S_{TP}) \tag{9}$$

A specialized binary macroscopic-microscopic method has been constructed in order to calculate the deformation energy which generates the fusion barrier. The total deformation energy is:

$$E_b = E_{Y+E} + E_{shell} + \delta P \tag{10}$$

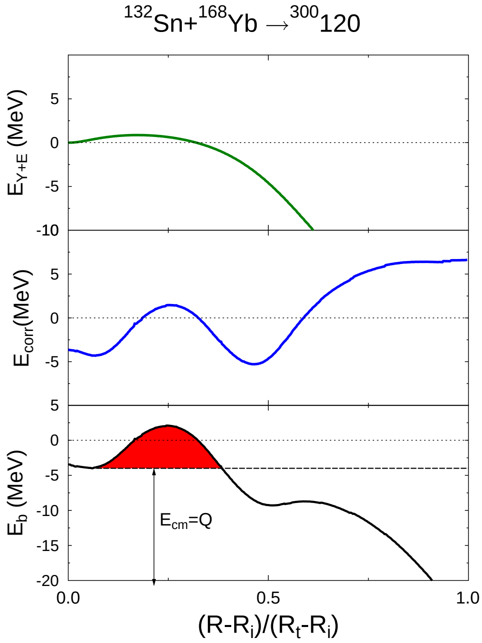

Figure 2: The macroscopic energy (upper part), the micropscopic corrections E_{corr} and the total barrier to be penetrated in the ^{132}Sn projectile reaction.

where E_{Y+E} is the macropscopic part, calculated as the Yukawa+exponential energy for a charged liquid drop type system, taken into account the finite range nuclear force potential. The microscopic part of the total deformation energy is composed by: E_{shell} which is the shell correction energy, and δP as the pairing term. The last two are calculated on the basis of the deformed two-center shell model, which produces the single-particle energy levels for a two partially overlapped nuclei configuration. The calculations are repeated for every step of the distance between centers R up to the complete overlapping corresponding to the formation of the compound nucleus. The levels which are obtained from the deformed two-center shell model are input data for the microscopic energy calculation. The shell correction are computed using the Strutinsky shell correction method, whereas the pairing residual interaction δP is obtained by solving the Bardeen-Cooper-Schrieffer equations.

In order to complete the dynamics of the process, the mass parameters B_{ij} must also be obtained. Here the q_i set takes into account all the free parameters defining the shape. The mass tensor is therefore geometry dependent as $B(b_P, \chi_T, \chi_P, R)$. These terms are computed by the cranking model, which is a quantum structure dependent procedure. Every term is directly influenced by the single-particle energy level stage in the overlapping process.

Finally one obtains the energy barrier which has to be penetrated. In figure 2 one can see the result for the synthesis of ^{300}120 following a fusion channel pair ^{132}Sn+^{168}Yb

The method has been applied to calculate the cross sections for the synthesis of Z=120 and Z=114. We chose these systems as they are the most probable next proton magic numbers after Z=82. The most promising sub-barrier fusion reactions are displayed bellow, together with the penetrability and cross section values.

The phase of the contract demonstrated that, despite the low cross section values, it is possible

Table 1: The sub-barrier fusion reactions with the highest cross section values for the synthesis of Z=120 and Z=114

For $^{300}120$:	
$^{132}Sn+^{168}Yb \rightarrow \ logP$=-8.27	σ =0.32 pb
$^{92}Sr+^{208}Pb \rightarrow \ logP$=-6.98	σ =0.12 pb
For $^{298}114$:	
$^{132}Sn+^{166}Gd \rightarrow \ logP$=-5	σ =0.48 pb
$^{90}Ge+^{208}Pb \rightarrow \ logP$=-5.35	σ =0.25 pb

to synthesize superheavy nuclei with sub-barrier fusion reactions. The advantage is to obtain a more stable final compound nucleus, very close to its ground state energy, thus lowering the decay probability. The magicity of the projectile or target proton number deeply influences the value of the cross section. Here this situation is illustrated by the Sn or Pb reaction partner presence in the highest cross section values.

Publications and Presentations at Conferences in 2014

Articles

1. D.N. Poenaru, R.A. Gherghescu, Journal of Physics G: Nuclear and Particle Physics, 41 (2014) 125104 **LabTalk article** http://iopscience.iop.org/0954-3899/labtalk-article/58987 si E-print at Cornell University, arXiv:1409.3155 [nucl-th]. http://arXiv.org/abs/1409.3155.
2. N.S. Shakib, R.A. Gherghescu, D.N. Poenaru, M.M. Firoozabadi, M.F. Rahimi, Romanian Journal of Physics, 59 (5-6) (2014) 515-528.
3. D.N. Poenaru, R.A. Gherghescu, Fission approach to cluster radioactivity, Pramana Journal of Physics, 82 (2014) to be published.
4. R. A. Gherghescu, D. N. Poenaru, Spontaneous fission of superheavy nuclei, Pramana Journal of Physics, 82 (2014) to be published.

Invited Presentation published in Proceedings

Invited Presentations at International Conferences

5. R.A. Gherghescu, D.N. Poenaru, Spontaneous fission of superheavy nuclei, International Conference ”75-years of Nuclear Fission: Present status and future perspectives”, 8-10 Mai 2014, Mumbai, India.

Referee, 2014

1. Journal of Physics G: Nucl Part Phys (SRI=1.849) 2 referee reports
2. Physical Review C (SRI=1.308) 3 referee reports

Project Director: Dr. Radu A. Poenariu-Gherghescu